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Sonification as Concurrent Augmented Feedback for Motor Skill Learning and the Importance of Mapping Design

John F. Dyer^{1,*}, Paul Stapleton² and Matthew W. M. Rodger¹

¹Queen's University Belfast School of Psychology, United Kingdom; ²Queen's University Belfast Sonic Arts Research Centre, United Kingdom

Abstract: In recent years, sonification of movement has emerged as a viable method for the provision of feedback in motor learning. Despite some experimental validation of its utility, controlled trials to test the usefulness of sonification in a motor learning context are still rare. As such, there are no accepted conventions for dealing with its implementation. This article addresses the question of how continuous movement information should be best presented as sound to be fed back to the learner. It is proposed that to establish effective approaches to using sonification in this context, consideration must be given to the processes that underlie motor learning, in particular the nature of the perceptual information available to the learner for performing the task at hand. Although sonification has much potential in movement performance enhancement, this potential is largely unrealised as of yet, in part due to the lack of a clear framework for sonification mapping: the relationship between movement and sound. By grounding mapping decisions in a firmer understanding of how perceptual information guides learning, and an embodied cognition stance in general, it is hoped that greater advances in use of sonification to enhance motor learning can be achieved.

Keywords: Auditory display, augmented feedback, concurrent feedback, embodied cognition, mapping, motor skill learning, sonification.

INTRODUCTION

Sonification of movement entails the use of technology to generate sound from human bodily motion [1]. Sonification has long been practiced in the domain of alternative music technology, in which musicians design interfaces which can be manipulated to create new musical sounds and forms for performances. Movement data is typically captured with the use of accelerometers, optical motion capture or force transducers and fed into a digital sound synthesis engine [2]. Modern high-speed computing allows the corresponding sound to be produced with very little latency, so the user is essentially controlling live sound in real time with the movement of his/her body. However in the last few decades, there has been growing interest in real-time sonification as a tool to aid in the enhancement of movement performance. It has found application in sport, in which athletes make use of sound information to more accurately time their actions [3, 4]. Additionally, therapeutic interventions have been designed involving sonification for rehabilitation of patients with motor disorders, which use sound cues to supplement degraded proprioceptive feedback and to promote reacquisition of movement skills¹ [5-9]. This article will briefly outline current understanding of feedback-enhanced motor

skill acquisition before considering recent sonification research as a springboard to discuss different aspects of sonified feedback. A conceptual approach for dealing with movement sonification as feedback for motor skill learning is developed throughout. This includes the potential of sonification as a useful (and underutilised) feedback choice and the need for greater attention to be devoted to the psychological issues associated with mapping design.

SECTION 1: MOTOR LEARNING AND AUGMENTED FEEDBACK

It is almost universally agreed that repeated physical practice of a task improves performance [10]. Indeed, functional performance of most complex everyday tasks (e.g. writing, driving a car) is generally impossible without extensive practice. Motor learning, according to Magill [11], is characterised by a “relatively permanent improvement in performance” of a given task as a result of physical practice. This is associated with relatively persistent structural alterations in the cortex which are identifiable post-learning [12]. Crucially, it has been shown that this ‘plastic’ reorganisation of the motor cortex takes place in direct response to afferent information from experience [13]. More simply, practice rewires the brain. Interestingly, the phenomenon of neural plasticity underlies both acquisition of motor skill in healthy individuals and reacquisition of basic motor abilities in victims of stroke [14]. As such, attempts to drive plasticity *via* practice of useful movements are the cornerstone of stroke rehabilitation strategies [15]. Therefore, feedback techniques which enhance motor skill acquisition are relevant and useful for both specialised learning (such as in sports or music) as

*Address correspondence to this author at the Queen's University Belfast School of Psychology, United Kingdom; Tel: +44 (0) 28 9097 4558; E-mail: jdye01@qub.ac.uk

¹ Motor rehabilitation can be considered a special form of motor skill learning, despite possible differences in the underlying neurology. At the behavioural level of description, the processes involved in healthy motor skill learning and motor rehabilitation may be highly similar.

well as re-learning more commonplace actions (like writing or walking) for rehabilitation.

During any kind of physical practice, a learner receives continuous feedback – sensory information about performance which can be used to make alterations and improve future attempts at the task. According to Magill [11], performance-relevant feedback can be separated into two main types: intrinsic feedback, which is performance information available to the learner as an inherent part of the task, and augmented feedback, which is provided through some kind of external mediator. Intrinsic feedback is available in several sensory modalities (visual, proprioceptive, vestibular, auditory and tactile) depending on the task, with each modality weighted neurally according to the reliability of the information it conveys [16]. The information contained in intrinsic feedback has a refining influence on subsequent trials, typically leading to improvement of technique. Indeed, for a skill to become autonomously performable, the learner must become acutely tuned into that information which specifies the parameters of the environment and ongoing actions necessary to achieve his/her movement goals [17].

The second form of feedback, augmented feedback, can come from a human instructor, or be provided *via* a technological display – again, in several possible sensory modalities. Augmented, or extrinsic feedback, when provided concurrently with practice (as opposed to terminally –after a trial has finished), has been shown to enhance speed of acquisition in a range of motor tasks [18]. It provides a live stream of performance information which would not normally be available intrinsically during standard practice – and can become a very effective guide. This results in significantly reduced rates of error relative to its absence [19, 20]. However, while concurrent augmented feedback may facilitate acquisition of a novel motor skill, several studies have found that learners tend to rely on it too heavily, and show a significant decline in performance when feedback is removed [21, 22], an effect known as the ‘guidance hypothesis’. By Magill’s definition, this means concurrent augmented feedback does not actually produce learning, except in a very specific scenario (that in which augmented feedback is available). This makes sense when we consider the “specificity of learning” hypothesis [23], which states that the effect of learning is greatest when conditions between acquisition and testing are closely matched. It may be that the availability of concurrent augmented feedback creates a very specific set of skill acquisition conditions. Learning may then be tied to these conditions and may not generalise beyond them. Sigrist *et al.* [18] suggest an explanation for this effect when it occurs in the context of augmented feedback. They propose that the learner automatically integrates the best of whatever afferent information is available to guide performance, sometimes to the neglect of the most fundamental of intrinsic feedback sources: proprioception. As Ernst and Bühlhoff [16] predict, the most reliable feedback is integrated. Concurrent augmented feedback potentially represents a veridical and extremely reliable source of performance information; it is expected that learners would lean heavily on it rather than intrinsic proprioception. Augmented feedback very often provides the learner with both a representation of his/her per-

formance *and* correct performance, allowing direct comparison [24, 25]. The immediate value of this information is high, as it allows the quick identification and correction of errors in performance. Crucially, it is typically available from the beginning of practice. At the initial stages of motor learning, intrinsic proprioceptive feedback is necessarily much less tightly coupled to goal outcomes, and is thus attended to less closely than augmented feedback. For motor learning to last, intrinsic proprioceptive feedback must however form part of the learner’s representation of the to-be-learned movement [26]. After removal of augmented feedback, proprioception becomes crucial for performance. The source of feedback upon which a learner had previously relied is no longer available to guide performance, and the learner must reweight to a comparatively unused source. The result is impaired performance-monitoring ability [27]. The ability to detect signals corresponding to both good and bad performance using internal monitoring mechanisms (*i.e.* proprioceptive feedback) is essential for competent performance outside feedback conditions.

The guidance effect and proprioceptive inattention during motor skill acquisition can dramatically undermine the facilitating effect of concurrent augmented feedback on learning. For concurrent augmented feedback to be useful, motor learning has to generalise beyond the acquisition phase; the same feedback is not usually available in the real-life context. Athletes, for example, do not have access to a graphical representation of their motor performance while they compete.

There have been experimental efforts to reduce the guidance effect of augmented feedback while still availing of some of its benefits for skill acquisition. Winstein and Schmidt [28] employed an arm flexion/extension task to compare the efficacy of constant feedback (given every trial) to intermittent feedback (*i.e.* feedback which was only available on some trials). They found that while acquisition was slower when feedback was provided intermittently, learners in this condition showed less of a guidance effect in a retention test. It has generally been found that feedback which is either intermittent, delayed, or is gradually reduced in frequency with skill acquisition can reduce the guidance effect [25, 29], but optimal procedures for administration of these techniques are still unclear – and might in fact vary by individual, type of task and even feedback modality [18].

The notion that effects of feedback may vary by the sensory modality in which it is presented is an interesting and fairly recent one. Sonification with the aim of conveying spatial or temporal information relating to movement performance is concurrent augmented feedback presented in the auditory modality. Sigrist *et al.* [18] point out however that most relevant experimental research on the effect of concurrent feedback employs the visual modality, or verbal instruction from a human coach. There is an assumption in much of the skill acquisition literature that effects of augmented feedback on motor learning, both facilitatory and inhibitory, should be universal across different sensory modalities. Magill [11] for example, deals with every kind of concurrent augmented feedback under the same umbrella, irrespective of modality. However, this assumption does not seem to hold true in all cases.

Recent research has attempted to determine whether differences between modalities in terms of feedback effectiveness exist. Sigrist *et al.* [30] examined task learning with concurrent augmented feedback presented in three separate modalities: visual, auditory and haptic. Participants were required to practice a rowing activity in a simulator with feedback provided on alternate trials *i.e.* on 50% of the total number of trials. In the auditory feedback condition, movement error was sonified, *i.e.* sonic variations were produced using measured deviation from the ideal movement profile - on both the horizontal and vertical plane, as well as rotational timing deviation. Visual feedback was provided on a screen to the side of the participant, showing the target oar trajectory with live performance superimposed on top. Haptic feedback was provided *via* robotic manipulation of the handheld oar, physically guiding the learner towards the target trajectory. The difference in movement error between feedback trials and non-feedback was very noticeable for the visual group. When feedback was present, participants showed very low error compared to when it was absent. A similar effect, although less pronounced, was observed in the haptic group. On retention trials, performance by these two groups was significantly worse than on earlier feedback trials (although some degree of learning relative to initial baseline was evident). Unlike the groups practicing with visual and haptic feedback, average performance in the auditory group did not vary based on the presence of feedback. Performance in this condition was highly variable between individuals and seemed to be entirely unrelated to the availability of augmented feedback information. This is an unusual pattern of performance to see in an augmented feedback experiment; scores in the visual and haptic conditions were much more typical in this regard in that performance was improved in the presence of feedback [21, 22]. An overall effect of learning (*i.e.* improvement in no-feedback performance from baseline) was not actually found in the auditory condition. This study at least stands as evidence of differences in the pattern of acquisition and retention between concurrent feedback modalities, but what it tells us about sonification as feedback *specifically* is an open question. *Does poor learning here compared to other feedback modalities suggest that sonification is a less useful form of concurrent feedback for skill acquisition?* One important thing to note when considering these results is that the authors acknowledge that their sonification prototype might not have been fit for purpose. Several participants reported great difficulty extracting the relevant performance information from their feedback. It could be that problems with the auditory condition in this experiment are not to do with sonification *per se*, but the relationship between the movement of the learner and the sound variables modulated (*i.e.* the “mapping”). This notion is important to keep in mind going forward and will be addressed in detail later.

In the next section, we will try to answer the question of the validity of sonification for motor learning, drawing support from the limited number of sonified motor learning experiments yet performed and some general theories of perception and feedback. The somewhat optimistic answer arrived at is that sonification as feedback can not only be effective for learning, but under certain conditions could be more efficacious than other modes of feedback.

SECTION 2: FACTORS THAT INFLUENCE THE EFFECTIVENESS OF AUGMENTED FEEDBACK IN DIFFERENT MODALITIES

As indicated above, the effects of feedback may not generalise across sensory modalities. In this section, we will raise the possibility that sonification as concurrent augmented feedback could, in some cases, be more effective for movement performance enhancement than traditional concurrent visual feedback. This may be due to fundamental intermodal differences in the delivery mechanism of the information contained in feedback. Sound information is perceived independently of most intrinsic sources of feedback, which means that it can be delivered (unlike the same feedback in the visual modality) without necessarily distracting attention from naturalistic performance monitoring.

The most obvious potential advantage of sonification as feedback over the more extensively-studied visual domain may be its ability to increase feedback information bandwidth without impairing processing of intrinsic sources of feedback. Audition as a sensory modality is largely dormant during motor learning – except in tasks which include sound as an intrinsic source of feedback (*e.g.* musical instrument training). This dormancy is especially true for the kinds of laboratory-friendly motor tasks employed in experimental research into concurrent feedback, *e.g.* isometric force production [24], bimanual coordination [27] and lever manipulation [25]. Kinetic impacts and interactions with the environment are the normal means by which the human body produces sound from motor activity, as the frequency of movements themselves are below the level of human hearing [31]. In the case of naturally noisy events, sound automatically becomes part of the amodal, unitary representation of the event which precipitated it [32]. This multisensory integration produces a synergy of information, resulting in richer, more accurate percepts of the environment [33]. Attaching audible sound to otherwise largely silent movement activity should therefore provide scope for conveying extra information about the movement’s quality, and should result in better online understanding of motor performance for the learner. This is of course dependent on carefully-designed, informative movement-sound mappings, as the learner must be able to perceive (at least implicitly) how his/her actions causally modulate the sound for the additional performance information contained therein to be useful. Further concerns on movement-sound mappings will be elaborated later.

Another key comparison which differentiates concurrent feedback presented in the auditory modality from the visual involves attention, and could allow for sonified feedback to be sensed without impairing sensation of intrinsic feedback. Concurrent visual augmented feedback typically employs a screen on which to display performance-relevant information [24, 34, 35]. This arrangement necessitates a certain gaze orientation for the learner – specifically, away from the limbs or body part in question and toward the display. The implication of this, visual distraction, could go some way to explaining the basic nature of the guidance effect as it manifests under concurrent feedback conditions. If the learner is attending to an external visual display, we can assume that his/her intrinsic source of visual feedback (the ability to

watch one's own motor performance directly) is impaired at the very least, if not gone entirely (depending on the physical arrangement of the lab and lines of sight). Instead of watching his/her limbs, the learner is typically encouraged to watch a graphical representation of the movements made by his/her limbs. On post-acquisition no-feedback retention tests, performance is impaired perhaps not *only* because intrinsic proprioception itself has been neglected, but because intrinsic visual feedback (which would otherwise integrate with proprioception) has also been displaced throughout. By comparison, sonification of movement does not require any specific gaze orientation for information pickup. The auditory system is shaped specifically for detecting information beyond the visual field-of-view, and this can be used to our advantage in the domain of feedback [36]. The implication is that in theory, the use of sound as feedback could ameliorate the guidance effect of concurrent feedback by allowing vision of the limbs during practice.

If we consider the finding that an external focus of attention can improve learning of complex tasks [37] another basis for informative comparison presents itself. Visual augmented feedback, particularly in the commonly-used form of a Lissajous plot (used to plot one movement variable against another using the same line), represents both an external object of focus and an abstraction of the task. Franz, Zelaznik, Swinnen and Walter [38] argue that Lissajous feedback fundamentally alters the nature of the task by consolidating a complex internal coordination pattern into a unified, external dot-moving task. Motor behaviour is transposed from the coordinate system of the limbs into the coordinate system of the graphical display to form a recognisable shape if performed correctly. In this way, visual feedback becomes the task in itself, semantically distinct and attended to separately from (and to the exclusion of) the kinematics of the motor task. Consolidation and abstraction could be the key to understanding how otherwise impossible-to-learn bimanual coordination patterns can be performed by participants under concurrent visual feedback conditions. Kovacs, Buchanan and Shea [35] found that when participants were denied vision of their limbs and left to attend exclusively to the Lissajous display, they were able to rapidly learn to produce extremely difficult coordination patterns (such as bimanual oscillations at a 5:3 ratio). They propose that a conflict between the coordinate system of the limbs and that of the visual display creates an attentional drain which is resolved by limb occlusion, allowing even greater performance enhancement. Clearly, this kind of concurrent visual feedback is at its most effective when the learner is deprived of some awareness of the fundamental kinematics of the motor task in question. Kovacs *et al.* [35] did not test retention without feedback, but one can be fairly confident based on related studies [27, 39] that a pronounced guidance effect would be evident. In the case of Lissajous-style feedback, what was originally intended as a guide to help learning an action has swallowed the task to be learned, replacing it completely.

Generally speaking, novices practice direct attentional control of the limbs when learning a new complex task [40]. It is only after a general representation of the to-be-learned movement has been acquired that an external object of focus becomes especially beneficial for performance. In expert performance, instructions encouraging an internal focus of

attention have been found to be detrimental to task performance and vice versa [41]. Sonification as feedback allows the learner to attend to his/her movements at the very early stage of practice, which could be beneficial in the development of basic competence for the novice [42]. However, to maximise learning later in acquisition, specific instructions encouraging a more external focus of attention may be necessary.

A crucial general requirement for effective concurrent feedback is not to overload cognition, as this can degrade performance on complex tasks and cause difficulty in integration of performance information [43]. As mentioned previously, performance under certain visual concurrent feedback conditions is enhanced by removing the cognitive drain of reconciling the coordinate systems of kinematics and display. This limits the incoming perceptual information to underlying – but unattended – proprioception and the augmented display information. The result is a guidance effect, which is not desirable for persistent motor learning. If we wish to reduce or eliminate the guidance effect, proprioception and awareness of the fundamental kinematics of the task must be brought into the fold, *i.e.* integrated into the internal model of task performance [11]. The use of movement sonification rather than visual display potentially allows for this. The crucial comparison here is that sonification as feedback does not entail an abstraction of the to-be-learned motor task in the same way as Lissajous feedback. Sound information can be perceived alongside fundamental intrinsic sources of feedback (vision and proprioception), thus functioning as a beneficial addition *on top* of naturalistic learning [4], rather than a distinct task in itself [44]. However this addition must be done without overloading the cognitive system. It seems clear that explicit attentional awareness of the limbs and their kinematics is at least something of a cognitive weight, if not exactly a burden in itself [35]. In order to allow for this, sonified feedback should be as minimal as possible in cognitive weight. In other words, one must be careful not to overload the system with the combination of vision, proprioception and augmented sound information. Although it is known that given clever sound design, several streams of sonic information can be disassociated from each other and attended to simultaneously [36, 45], the task of integrating them with the corresponding dimensions of motor performance could represent a cognitive drain of the same manner described by Kovacs *et al.* in the domain of vision. Multidimensional movement error sonification runs this risk highly, as demonstrated by Sigrist *et al.* [30].

Keeping the cognitive load imposed by feedback as low as possible has been shown to be an effective strategy in some sonification studies. Mononen, Viitasalo, Kontinen and Era [46] provide evidence of the value of simplicity through an experiment in which they sonified one-dimensional aiming error in shooting practice. Not only did they find no guidance effect upon withdrawal of auditory feedback, but the group which had received 100% sonified practice trials actually performed significantly better two days later than 50% feedback and control groups. The sonified feedback provided an informational boost to the learners, who were able to form a more accurate online percept of their performance during acquisition. In this task, awareness of intrinsic proprioceptive feedback was not supplanted by monitoring of a visual display, nor was attention distracted

by the effort of integrating informationally-dense feedback with performance. Rather, proprioception was allowed to remain an integral part of the learning process. This means that during acquisition, proprioception was always a part of the process of performance monitoring. The link between the goal of the task (shooting accuracy) and the bodily movement employed to achieve it was allowed to develop naturally, and performance was boosted by the sonified feedback provided. Since better performance was reached with the full inclusion of proprioception, no decline in performance was associated with withdrawal of augmented feedback.

The human motor system technically contains more room for output variability than is necessary for most motor tasks. Each moving body part contains several possible axes of movement, or degrees of freedom, for deployment in the performance of a motor task. The fact that there are more possibilities for movement than is necessary to complete a task effectively has often been characterised as 'redundancy', or 'abundance' [47]. The problem for a learning nervous system is to identify the combinations of muscular patterns (among these abundant degrees of freedom) that will consistently and stably achieve the performance goals. In other words, the problem is to map the range of limb movements that can be made to the narrower range of movements that will lead to successful performance of the task at hand.

It is important to consider the abundance of degrees-of-freedom and their utilisation in everyday skilled performance for sonification design (and indeed, augmented feedback design in general). It may not be necessary, or even prudent to feed back the activity of all the degrees of freedom involved in a task. For maximum informational efficiency, sonified feedback should specify or draw attention only to the stable invariants of good performance, while allowing the rest of the degrees of freedom of the motor system to vary as required. For example, in a bimanual coordination task, the stable invariant of good performance is the timing of relative position of the hands [48]. What the rest of the motor system does is free to vary without directly constraining task completion, and thus need not be fed back.

Both Todorov *et al.* [19] and Wulf and Shea [43] argue that feedback which provides information about the movement of the end effector (*i.e.* the point of the body which is most directly responsible for task performance – the fingertip in a pointing task, for example) is the most effective. This information is both cognitively economical and high-level, in that it only needs to describe the outcome of motor performance, and doesn't prescribe exactly how the underlying degrees of freedom should interact to produce this outcome. This approach has also been found to be effective for sonification of reaching movements in stroke survivors [49]. It has long been established that accomplished motor performance in a given task does not necessarily require rigid adherence to a set of biomechanical constraints on the degrees of freedom, that is, moving the same muscle groups in exactly the same way every time the action is performed [50]. Rather, the motor system should be allowed to organise itself. The example of Bernstein's hammering factory worker (who was able to consistently hit his target despite wide variability in his degrees of freedom between hits) illustrates well how the

redundancies in the motor system can be allowed to vary widely around one invariant: the repeated effective completion of the task. Exploiting this variability is a hallmark of flexible skilful performance in a variety of domains, for example cello-bowing [51]. Wulf and Shea [43] make the case that a focus on the lower levels of motor control (*i.e.* exact deployment of the degrees of freedom) is cognitively demanding, and is detrimental for both complex skill acquisition and subsequent performance. Additionally, directing the learner's attention to the *effects* of his/her motor activity is akin to inducing an external object of focus, which creates additional benefits [37].

The intrinsic proprioceptive signal corresponding to correct task completion *is present* in novice performance; the learner is simply as yet untrained to perceive or recognise it. As such, concurrent augmented feedback should be used to highlight this signal in learner performance and allow comparison between current performance and the goal. This fits with an ecological approach to motor skill learning, which has been termed 'education of attention' [52]. For sonification design, we suggest that it is important to have a clear understanding of what the goal of the task is, and provide sonic information on performance only as it relates to components of the task which should be stable and not vary with correct performance. The motor system of the learner should thus be encouraged to self-organise around attempts to adhere to these invariants. No performance kinematics should be prescribed, or even included in sonification unless they are essential to correct task completion.

Ronsse *et al.* [27] provide some indication of how effective this approach can be for motor learning, and a rare example of sonification contrasted with concurrent visual feedback on the same task. They trained participants on a difficult bimanual coordination task (90-degree out-of-phase wrist flexion) with either concurrent augmented visual or auditory feedback. The auditory feedback design used by the authors was effectively minimal, and only provided information on the relative timing and direction of the limbs. Participants heard either a high or low-pitched discrete tone depending on the position of their wrist, which was triggered by reversals in direction. Information relating to relative direction is believed to be the most important task-relevant signal for persistent learning in bimanual coordination tasks [48]. Timing of relative position is the invariant associated with correct performance here, and no other movement variables need be considered in feedback. Pitch is well-suited to display this kind of relative, categorical information, as will be discussed later. Learners were able to compare the sounds produced by their performance to a guide sound which corresponded to correct performance and was repeated periodically during practice. Visual feedback was presented to another group *via* a live Lissajous figure (which draws a circle from perfect performance of a 90-degree out-of-phase pattern). Both groups practised to equal asymptotic performance (which arrived slightly earlier for the visual group) and were assessed on a no-feedback retention trial. Interestingly, differences were found in the guidance effect between groups. The visual group displayed a significant increase in absolute error without feedback – almost back to pre-training levels; a textbook guidance effect. The auditory group did not, maintaining performance close to levels in trials with feedback.

Hence, in their study, sound was more effective as feedback than visuals for enhancing learning.

Ronsse *et al.* [27] speculate on the reason for the apparent primacy of sonification as feedback in their study. They suggest that the sound produced during practice is attended to directly in the early stages of acquisition, during which time it is integrated with proprioception, mediating an internal representation of the required timing of the task. They recorded (*via* fMRI) comparative deactivation in neural areas associated with sensory monitoring following the acquisition phase for the sonification group, which hints that the auditory feedback was no longer actively monitored as a guide for performance. Instead, the feedback may have been internalised and become part of the learners' own egocentric process of performance-monitoring towards the end of acquisition. In no-feedback retention, the sound produced by good performance may actually have been internally simulated to further guide performance in the absence of an extrinsic source. This notion highlights another useful aspect of sonification as concurrent feedback. It is possible to recall the sounds produced by feedback during acquisition to be used as a guide for subsequent good performance in no-feedback retention. Again, this is likely only possible with a cognitively light form of auditory feedback (making it easy to recall) and an intuitive, memorable action-sound mapping, which will be covered in detail in the next section.

Besides the discussed perceptual-motor and cognitive factors, there are additional psychological processes that may mediate the effectiveness of augmented feedback in motor learning. Motivation and task engagement are important, yet underappreciated influences on motor learning [53]. If a learner is motivated and fully engaged, they will allocate greater attention to the task, and seek to improve as quickly as possible. The impact of motivation on learning is beneficial, but can also be hard to induce in an experimental setting. One way to increase task engagement in a motor learning experiment is through feedback itself. Certain kinds of visual displays such as Lissajous plots are intrinsically motivating because they present a challenge to produce a certain shape. As long as the cognitive demands of the task are not too high, challenging the learner can enhance motivation and therefore, learning [43]. Another relevant aspect of motivation is the possibility of reward. It has long been established that actions which have favourable outcomes are likely to be repeated, as the organism in question will be motivated to seek out another reward [54]. Sonification in particular allows the design of feedback which is rewarding, thanks to its association with music. Musical listening can induce feelings of pleasure in the listener [55], which are correlated with activation in neural areas associated with pleasure and reward [56]. Digital sound synthesis enables the incorporation of musical sounds into feedback which (with good design) can produce something that is ultimately pleasurable to listen to. Learners will thus be motivated and eager to continue practice, which will have beneficial effects on attention and learning. Musical sonification can additionally induce feelings of self-efficacy in the learner, as the power to produce pleasurable music is made available to them. This is again likely to stimulate greater task engagement [57]. Wallis *et al.* [58] provide a good demonstration of this approach in a small-scale motor rehabilitation study involving stroke pa-

tients. They incorporated several aspects of musical composition into sonified feedback in a reach-to-grasp task, which promoted smoother, more effective reaching movements in their three participants.

In summary, there are some qualities specific to sonified feedback which can potentially effect a greater enhancement of learning than feedback presented in other modalities (*e.g.* vision). Sonified feedback which draws attention to the aspects of performance that should be corrected can be perceived whilst maintaining attention on all intrinsic sources of feedback, and may well integrate more fully with intrinsic sources, forming a more robust and persistent framework for learning. It has also been noted that feedback which is intrinsically motivating or pleasurable can have additional enhancement effects on motor learning, above and beyond what is possible with basic informational feedback. In the case of sonification, this may require additional expertise in digital sound production and musical theory to implement, but the potential is there and waiting to be exploited in a controlled motor learning experiment. The exact nature of musical sonification is something which needs to be considered very carefully. For example, one of the participants in the Wallis *et al.* [58] experiment cited above showed less of an improvement after practice with feedback ostensibly because he did not particularly like the genre of music used. The relationship between the movement of the learner and the sound fed back to them is an area worth considerable attention, and is the subject of the next section of this review.

SECTION 3: MAPPINGS AND AESTHETICS

The motor learning literature is not replete with empirical tests of concurrent sonification as feedback. Controlled assessments of its effectiveness are rare, and do not always provide clear recommendations for future implementation. For example, Sigrist *et al.* [30] reviewed three modalities of feedback (visual auditory and haptic) in an attempt to probe how general principles such as the guidance effect compare on the same task. A clear problem however, emerged in the auditory condition. Few participants were able to extract helpful performance information from the feedback as it was presented to them. No enhancement in performance was observed with the addition of this concurrent feedback relative to terminal (post-trial) feedback during acquisition or retention, *i.e.* sonification did not enhance performance. This was perhaps not because the relevant information was not present in the feedback, or not reliable, but (at least partly) because of how this information was presented through sound. The learner needs to perceive and understand how his/her actions produce sound, otherwise the value of sonification as concurrent feedback evaporates. This is essentially what is meant by "mapping"; the relationship between the learner's movement and the output of the system – the feedback system, that is. This essential aspect of movement sonification can be notoriously elusive, and no unified set of principles currently exists by which mapping decisions should be guided. In this section, we will highlight some tricky mapping choices currently faced by movement sonification designers, and also argue that sonification as feedback needs to consider more than just the most basic or reduced informational content representable by sonic feedback. Mapping and sound design can be approached from many different angles,

including experimental Psychology, Ecological Psychology, Philosophy of Mind, digital musical interaction and aesthetics. As such, this section will take a broad multidisciplinary perspective.

There are a number of issues with action-sound mappings for feedback that are distinct from the same kind of feedback provided in the visual modality. Visual feedback often comes in the form of a live graph displaying some parameter of movement kinematics drawn as a line [24, 34]. This is easy for the learner to understand because of its ratio level of measurement and clear, quickly-interpretable display. For example, in a learning exercise which uses a graph to display absolute position over time, the raw data associated with the learner's limb displacement is directly transposed from the coordinates of the body in space to the coordinates of the visual display, with little loss in fidelity. On this hypothetical graph, one line followed by another at double its height is straightforwardly interpreted as meaning that double the distance in that direction was moved the second time. If we try to imagine how this same information could be displayed using sound, we are confronted with a myriad of potential choices. Which is the most appropriate dimension of sound with which to display the information? Effenberg [31] (p. 53) correctly asserts that "an almost endless amount of options are available to transform data into sound". There definitely exists a problem of *too much choice*, and in the absence of a pre-existing framework by which to distinguish these choices, there is a risk of making mapping decisions that are ineffective or even detrimental to motor learning.

An example of an auditory variable to which movement can be mapped is pitch. This is perhaps the most common mapping choice for sonification in general, having been employed to represent a wide variety of data types [59]. Controlled variation in pitch has previously been used to represent movement in sonified feedback investigations [46, 60, 61], and would certainly occur to a researcher as a logical possibility to effectively represent changes in a value like position. Pitch can go up and down (in Western musical description) and so can position. How though, can pitch convey the relationship between one absolute positional change and another exactly twice as great? This is easy in the visual modality, as previously described. We cannot simply map positional data directly onto sound frequency, as humans do not perceive frequency differences as readily at high frequencies as at low [62]. Even using a logarithmic mapping function is not a fix, as the relationship between physical acoustic properties of the sound and its psychological representation is both non-linear and highly subject to individual differences [63]. Contrasting this with the more intuitively-understood ratio information conveyed by a graphical display highlights the impropriety of using pitch variation to display this kind of information. The appropriate variation in pitch (if there is one) is elusive here, though a workable mapping could perhaps emerge with extensive prototyping and user familiarisation training. Norman [64] discusses some general principles of mapping design, and argues that mapping an additive dimension (like absolute position) to musical pitch is misguided, as pitch is not additive. Tempo, for example, may be a more appropriate choice. It is easy to understand what "twice as fast" means, whereas "twice as high in pitch" may make less intuitive sense.

That is not to say that musical pitch is off the table for representing bodily motion, far from it. Based on an embodied account of cognition [65, 66] and the obvious relationship between music and movement, there is much scope for the use of pitch in augmented feedback systems, although perhaps only in a different kind of task without a requirement for displaying absolute quantities in feedback. The case has been made that musical melody, *i.e.* pitch variation is understood *via* intuitive mapping onto the body of the listener [67], and experimental evidence seems to confirm this. Rusconi, Kwan, Giordano, Umiltà and Butterworth [68] tested response times to high and low tones using a computer keyboard and found that responses were faster when the target key for a "high" tone was located at the top of the keyboard (*i.e.* the top letters row) than if it was the at the bottom (space bar). They argue that this finding of stimulus-response compatibility indicates a universal phenomenological experience of high pitched sounds occupying a higher space than their lower frequency counterparts. A non-absolute variable might be more suited to pitch as feedback. We can tell experimentally that the conceptual mapping between pitch and distance/height does make sense, but only in relative terms - listeners can tell when one pitch is higher than another. The suitability of pitch to convey relative information, rather than absolute, has been successfully employed by Ronsse *et al.* [27] to sonify relative position in bimanual coordination. This mapping worked because there was a good fit between the requirements of the task and the information that the sound variable was suited to carry. Using two discrete pitches to represent two positional orientations is also a mapping metaphor that makes sense.

Certain sonic variables (*e.g.* pitch, loudness, tempo etc.) are clearly more suited to the display of certain kinds of information than others [45, 69], but what about certain kinds of movements? Gibson's [70] theory of ecological perception holds that there are invariant relationships between sensory information detected by the organism and the associated event in the environment. Experience and implicit knowledge of these relationships is what allows us to identify qualities of a sound source. A human listener can perceive an incredible amount of source-relevant information from a range of features inherent in a sound event, including its direction [71], size [72], movement speed [73], material composition [74] and even some biomechanical behaviours of the sound-making individual [75]. Sonic information informs the perceiver about the nature of the noisy event, but more importantly, it allows us to act on it. Affordances, or opportunities for action [70] can be present in sound. In other words, certain sound stimuli invite or encourage particular forms of movement. This phenomenon is particularly evident in dance music [76, 77], but has also been seen in constrained sensorimotor synchronisation experiments. Rodger and Craig [78] report an experiment in which participants were required to synchronise wide, planar hand movements to a sonic pacing stimulus. They found that the type of sound selected for the pacing stimulus had an effect on the trajectory of synchronisation movements produced by participants. Continuous pacing sounds encouraged more harmonic/sinusoidal synchronisation movements than discrete sounds, which were associated with more discrete movements. Despite participants only receiving instructions to

keep their movements synchronised to the temporal interval, measurable differences in movement style emerged depending on the type of sound involved. This is likely due to implicit knowledge about ecological sound production, or rather, awareness of invariant sound-action relationships concerning continuous vs. discrete sounds in the environment. Participants automatically and unconsciously expressed that awareness through movement in this scenario.

The required movement of the learner must be considered in sonification mapping design. As a simplified example, large, slow movements could be mapped to continuous sounds and fast, immediate movements mapped to discrete sounds. If the information contained in sonified feedback and the actions which produced it can be linked using the same kind of invariants we expect to encounter in the environment, the system can be fundamentally understandable from the outset. Danna *et al.* [79, 80] provide an example of this in action. They sonified handwriting using feedback designed to sound like an object rubbing against a hard metal surface. Smooth, fast pen movements were accompanied by a low-pitched rolling sound and jerky, slow movements produced high-pitched squeaks and percussive sounds. The sound feedback is modulated by movement in the same fashion as one would expect to find in the real world and as such, this mapping requires very little familiarisation time. The ecological approach to perception [70] has provided much inspiration to sound designers in the field of auditory display [81, 82] and Walker and Kramer [83] (p. 150) describe it as a “good starting point” for design; however investigations such as these are rarely accompanied by empirical motor learning experiments.

Norman [64] pushes for the adoption of “natural mappings” in the design of interfaces in general, but the concept is also applicable to sonification as feedback. This concept entails mapping metaphors which are intuitive to the user based on perceived similarities in form between the required action of the user and the expected outcome of the system. One example of a so-called “natural mapping” is that of an up and down slider to control volume on a stereo. This control mapping is intuitive or “natural” because loudness is typically thought of as “additive”. An up and down slider fits with this because increases in quantity are often associated with a level increasing vertically (*e.g.* filling a glass with water, adding books to a pile). Caution should be used when interpreting this mapping metaphor for sonification design however, for the same reasons mentioned earlier for the dimension of pitch – the relationship between loudness (as measured by sound pressure) and its psychological representation is non-linear and subject to variation among individuals. In the realm of product design however, it serves perfectly well. Interfaces designed in a certain way afford certain actions [84] and certain types of sound afford different kinds of actions [85, 86], so a task which invites the user to interact with a system in a way that is aligned with (or in some way analogous to) its sonic output will create an interface which is easier to master. If natural mappings are employed in sonification design, motor learning could be enhanced. Firstly, systems would require less familiarisation time. Secondly, feedback need not overwhelm intrinsic proprioception – rather, it would complement it. According to Norman, natural mappings take advantage of “physical

analogies and cultural standards” (p. 23) to create an action-equivalence between the movement of the user (through the interface) and the output of the system. It is perhaps more helpful here to think of sonified feedback as an auditory analogue of movement, rather than a medium in which to display otherwise abstract data, as is the tendency in much of the literature concerned with sonification and mapping [1, 45]. Bodily movement is inherently meaningful to the mover [66]. The task for a movement sonification designer is not to impose sonic form and meaning on a stream of raw data, but to support and draw upon that which is already present in bodily movement.

Perceived sonic form and motion must also be considered. There are motional forms perceivable in sound as much as there are in the visual domain [65, 87], and these should map as closely as possible on to movement. Movement is inherent in music. In the case of music production, this relationship is explicit. To play traditional musical instruments, the musician must transduce movement into sound *via* the physical excitation of reeds, strings and membranes. The tight deterministic mapping between action and sonic outcome is what makes these interfaces learnable [88]. Although the technology commonly employed in sonified motor learning experiments allows us to electronically surpass the need to excite a resonant object to make sound, there is no reason why the same musical principles cannot apply. Kleiman-Weiner and Berger [3] provide an excellent example of sonification based on this line of thinking, in which they likened a golf swing to bowing a cello, and (after some prototyping) designed their mapping accordingly. The authors clearly see a common structural form between the two activities, and suggest that their prototype could potentially be used to enhance swing performance in novice golfers. However an empirical evaluation of this potential has not yet been done. Considering a learner using sonified feedback as akin to a musician playing an instrument will likely be a fruitful thought exercise as far as mappings are concerned.

A selection of theoretical perspectives can at least provide inspiration and a theoretical rationale for pursuing a certain style of sonification mapping. However, a major difficulty of designing movement sonification mappings for experimental use is that empirically-backed rules/recommendations do not exist - and where they do, they are task-specific. The field of feedback in motor learning and control is as broad as one would expect, given the scope of applicability. New understanding of augmented feedback strategies could find use in almost any facet of human life which requires skilful action, including but not limited to: sport and exercise, musical training, motor rehabilitation, product design, human-computer interaction and any other kind of motor skill acquisition. Researchers have employed a correspondingly wide variety of motor tasks in order to experiment with sound and movement, and the most-effective mapping can rarely be inferred from the literature - except from previous research which has employed a similar task. As a result, researchers often intuit their own bespoke mappings for the motor task of interest, contributing another piece to the already scattered and fragmented literature. The state of the literature makes it difficult (at this point) to assess the suitability of sonification as concurrent augmented

feedback for a novel task or skill to be trained. If a given experiment (such as Sigrist *et al.*, [30], which sonified multi-dimensional error in a rowing task) shows that learners perform worse under sonification conditions than when using feedback in other modalities, it does not tell us that sonification is less effective than these other options as a general rule. It does not even tell us that sonification is less effective or appropriate to use as feedback for this particular task. There could theoretically exist a workable action-sound mapping for that task which conveys the relevant performance information to the learner in an easily-understandable way, and learning could be enhanced.

Designing a sonic mapping is not easy. Kleiman-Weiner and Berger [3] tested a selection of sonification prototypes before deciding on a sound mapping which most effectively represented the action of a golf swing. This highlights the need for a sonification design process that is extensively iterative. The ideal mapping may not be immediately obvious, and prototypes should be developed before committing to implementation. Walker and Kramer [89] caution that even mappings which appear to make sense to the researcher may not necessarily make sense to the participant. User-testing is a must. Beyond concerns of individual mappings, there is a great need for an overarching theoretical framework for movement sonification mapping design. This would serve to constrain mapping design for given movements to a more narrow range of workable possibilities, thus speeding up the implementation process and sidestepping the need to test a potentially vast selection of mapping prototypes.

CONCLUSION

Movement sonification has a wealth of as yet largely underutilised potential as concurrent augmented feedback for motor learning. In theory, sonification could perhaps be *more* effective for movement performance enhancement than the more traditional visual concurrent feedback in certain tasks. The nature of sonification as feedback allows it to be perceived independently of intrinsic sources of feedback and simulated in its absence, potentially alleviating the guidance effect. However the evidence does not yet exist to claim this with certainty. Carefully-considered sound design enables the implementation of feedback which integrates naturalistically with movement, inducing multisensory integration and more accurate percepts of performance.

Mapping philosophy is an area of feedback design which is often neglected, or only given cursory attention in motor learning experiments. Mapping is particularly important in sonification for motor learning and rehabilitation – it can make or break an intervention. Ideally, sonified feedback can be designed to be pleasurable to listen to and intrinsically rewarding. Resulting positive affect could have positive implications for motivation and hence, learning. In the domain of visual feedback, providing accurate kinematic information on one of several kinds of graphical display is normally sufficient to enhance performance, but an equivalent set of guidelines or proven strategies have not been established for the presentation of the same information through sound. Sonification for motor learning is a young field, and the vast array of untested mapping choices can be intimidating. This is slowly changing, however. With the ever-increasing pro-

liferation of technological literacy and computing power, it is becoming progressively easier to implement and test sonification prototypes, and the field of auditory display has already made some significant advances in establishing guidelines for sonic mapping of more abstract data. The mapping of human movement data for the purpose of feedback has received less comprehensive attention, but this review can hopefully point an interested researcher in the right direction.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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